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ULTRA-HIGH STRAIN RESPONSE OF ELASTOMERIC POLYMER DIELECTRICS

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ABSTRACT

The strain response of dielectric elastomers sandwiched between compliant electrodes was studied. These electroactive polymer artificial muscle (EPAM) materials show excellent overall performance and appear more attractive than many competing actuator technologies. Based on the available data, the actuation mechanism is due to the free charge interaction of the compliant electrodes, enhanced by the dielectric properties of the elastomer (Maxwell stress). Strains over 200%, actuation pressures up to 8 MPa, and energy densities up to 3.4 J/cm^3 have been demonstrated with silicone rubber and acrylic elastomers. Response time is rapid, and the potential efficiency is high. The fabrication of EPAM actuators can be simple and low cost. A wide range of small devices have been made, to demonstrate the potential of the technology and reveal more about performance and fabrication issues. These devices include bending beam actuators for scanners and clamps, diaphragm actuators for pumps and valves, stretched-film actuators for electro-optics, and bow actuators for muscle-like actuators for small robots and other micro machines.

INTRODUCTION

Motivation

In small-scale systems such as microrobots and micromachines, conventional electromagnetic technologies generally perform poorly due to physical scaling effects and fabrication difficulties. Such small-scale systems could benefit from improved actuators. There has been much recent interest in electroactive polymers as actuator materials. In general, polymers are attractive as actuator materials because they are lightweight, easily fabricated in various shapes, and low cost; in addition, their properties can often be modified as desired by various chemical means. Within the general category of polymers, the many different possible approaches to actuators include electrostrictive polymers,[1-5] piezoelectric polymers,[6] shape memory polymers,[7] electrochemically actuated conducting polymers,[8-13] and polymer-based air-gap electrostatic devices.[14]

Actuators and actuator materials have several important performance parameters including energy density, specific energy density, strain, actuation pressure, response time, and efficiency. To this list must be added practical considerations such as environmental tolerance, fabrication complexity, and reliability. Given this range of parameters, it is not surprising that individual applications depend more heavily on only one or a few of the parameters. Nonetheless, we consider a useful actuator technology to be one with good overall performance, as opposed to excellent performance in one or two parameters and poor performance in others. This view is supported by the dominance of electromagnetic technology on macro scales, where electromagnetic actuators have good overall performance, as well as by the good overall performance of natural muscle.

This paper describes an approach to electroactive polymer actuators that uses the deformation of elastomeric dielectrics. In studies of this approach since 1992, SRI has demonstrated overall performance similar to or exceeding that of natural muscle in many respects. Because it uses

elastomers and has performance comparable to that of natural muscle, we refer to this approach as electrostrictive polymer artificial muscle (EPAM).

This paper is organized as follows: We first describe the basic principal of operation of the technology. Next, we describe the measured performance of several materials, including a recently identified acrylic that is capable of extremely large strains (more than 200%). We then describe issues related to the fabrication of devices based on this technology. Next, the design, fabrication, and performance of specific actuator embodiments are described. Finally, we summarize and discuss the potential applications of this technology and the research challenges that remain.

Background

The principle of operation of the EPAM technology is shown in Figure 1. An elastomeric polymer is sandwiched between two compliant electrodes. When a voltage difference is placed across the top and bottom electrodes, the polymer is squeezed in thickness and stretched in area. We have previously shown that the principal cause of this stress condition and the resultant deformation of the polymer is the electrostatic forces of the free charges on the electrodes.[15] It is useful to introduce an analytical model that relates the observed stresses and strains to the applied voltage.

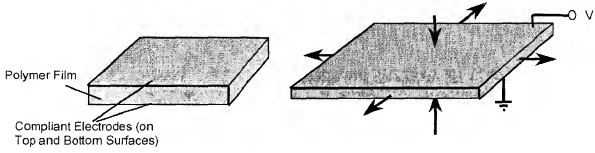

Figure 1. Principle of Operation of EPAM; Film Expands in Area and Contracts in Thickness

The derivation of the electrostatic model is described by Pelrine, Kornbluh, and Joseph.[15] The actuation pressure, p, is given by

$$p = \varepsilon \varepsilon_o E^2 = \varepsilon \varepsilon_0 (V/z)^2 \quad , \qquad (1)$$

where E is the electric field, ε is the dielectric constant, ε_0 is the permittivity of free space, V is the voltage, and z is the polymer thickness. Note that this pressure is greater by a factor of 2 than that arising from the commonly used equation for Maxwell's stress in a dielectric of a rigid plate capacitor. The greater pressure is due to the compliance of the electrodes, which allows both the forces of attraction between the oppositely charged electrodes and the forces tending to separate the charges on each electrode to couple into the effective pressure normal to the plane of the film.

For small strains with free boundary conditions, the polymer thickness strain, s_z, is given by

$$s_z = -p/Y = -\varepsilon \varepsilon_o (V/z)^2/Y \quad , \qquad (2)$$

where Y is the modulus of elasticity. The model for large strains with more realistic constrained boundary conditions, such as those required to drive a load, is more complex. However, this simple case illustrates the influence of the electrical and mechanical properties of the polymer on

actuation performance. The model also assumes that the elastomer is an ideal rubber, that is, that the rubber is incompressible and has a Poisson's ratio of 0.5.

One of the more useful metrics for comparing actuator materials, independent of size, is the energy densities of the materials. The actuator energy density is the maximum mechanical energy output per cycle and per unit volume of material. For small strains with free boundary conditions, the actuator energy density, e_a, of the material can be written as

$$e_a = Y s_z^2 = (\varepsilon \varepsilon_o)^2 (V/z)^4 / Y \quad . \tag{3}$$

Conventionally, the elastic energy density $e_e = \_ Y s_z^2$ is often used. However, for large strains with a linear stress-strain relation this formula must be modified because as the thickness strain becomes increasingly negative, the film flattens out and the area over which the pressure must be applied increases. Nonlinear moduli, common for elastomers at high strain, further complicate the energy density formula. A detailed derivation for large strains gives a more general approximate formula for the elastic energy density of materials[16] as

$$e_e = - \_ p \ln [1 + s_z] \quad , \tag{4}$$

where p is the actuation pressure given by Equation 1. This equation agrees with the more common formula at small strains but is significantly higher for strains greater than 20%.

With electronics that drive at constant voltage, Equation 4 is ambiguous because p changes throughout the stroke as the thickness of the film decreases and the electric pressure increases. This effect is not an issue with small-strain materials such as piezoelectrics because the fields are essentially constant with a constant applied voltage at small strains. With large-strain materials the effect can be dramatic, and we need to distinguish between the fundamental material performance, assuming optimal electronics, and the performance one expects to see with constant voltage. The simplest material assumption is that the breakdown strength of the material does not change throughout the stroke, so that the maximum field pressure should be used in Equation 4 when estimating peak performance with optimal electronics.* For constant voltage drivers, however, a more detailed analysis indicates that the $\ln[1 + s_z]$ term in Equation 4 should be replaced by $(s_z + 0.5\, s_z^2)$.

Various electrostrictive mechanisms can be considered for polymer actuators. While the mechanism for EPAM relies on electrostatic forces, the performance of an EPAM actuator is critically determined by the electrical and mechanical properties of the polymer. In particular, EPAM performance depends on the macroscopic permittivity of the polymer as well as on its modulus of elasticity. Therefore, it is appropriate to consider EPAM as an electrostrictive polymer technology.

EXPERIMENT

Experimental Procedure For Measuring Material Performance

The experiments in our study were designed to measure the response of different polymer materials to applied electric fields.

The measurement of the performance of different polymer materials is complicated by the fact that several of the polymer materials evaluated are relatively soft (have elastic moduli below

*Real electronic drivers could closely approximate the optimal electronics by servoing the applied voltage according to the sensed strain.

1 MPa). Therefore, the constraints on the polymer film must be carefully controlled. The situation is further complicated by the fact that film samples are often quite thin. We therefore used optical methods to measure the strain condition of the polymer film.

The measurement configuration is shown in Figure 2. A thin film of a polymer is stretched uniformly across a circular hole in a rigid frame. Electrodes are applied to a relatively small circular area at the center of this frame. When a voltage is applied to the electrodes, the film between the electrodes expands in area and contracts in thickness. This expansion in area is measured with an optical microscope, a video camera, video digitizing hardware, and digital measurement software. The software measures the amount of motion of identifiable features on the surface of the electrodes (such as texture features) when a voltage is applied. By comparing the location of the features at a given voltage to the locations at zero voltage, we determine the in-plane strain at a given voltage. The magnification of the microscope and resolution of the video camera are such that a single pixel represents only a small portion of the observed motion. Most measured motions were on the order of tens of pixels. Photographs of one such experiment with 3M's* VHB 4910 acrylic adhesive are shown in Figure 3.

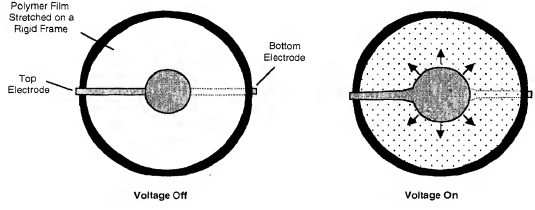

Figure 2. Experimental Setup (Top View)

Voltage Off Voltage On

Figure 3. Photo of VHB 4910 Acrylic Showing Approximately 200% Area Strain (–66% Thickness Strain)

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The effects of creep and mechanical hysteresis on the measured strain were minimized by obtaining the strain reading immediately following the application of the voltage. The voltage was brought to zero between each measurement. Any effects of electrical hysteresis on the strain measurement were assumed to be insignificant compared to the total measured strain.

Films of the polymers were prepared by dissolving the uncured polymer in a suitable solvent, such as naphtha for the silicone rubbers (polydimethy siloxane). The polymer solution was then spun onto a disk at a speed appropriate to give a thin uniform coating. This operation was performed in a clean room to minimize the introduction of particulates into the film. The sample was then allowed to dry, to remove the solvent. Certain polymers were further cured at elevated temperatures according to the manufacturers' specifications for a complete cure. Film samples varied from 1 to 100 μm in thickness, depending on the properties of the film. In general, film thickness was chosen to give a maximum sustainable voltage between 1 and 10 kV.

The acrylic and polyurethane films are commercially available in rolls. These films were found to have good uniformity. With the acrylics, however, the thickness of the best performing films is fairly large (typically 0.5 to 1 mm). Thus, it was necessary to stretch these films considerably, by a factor of 3 to 4 in both planar directions. While a large prestrain is necessary in the film, due to the large actuated strain, the large prestrain also changes the elastic properties of this film, bringing it into a stiffer regime with lower viscoelastic losses. Finally, it has been observed in both acrylics and silicones that a large prestrain can actually increase the dielectric strength of the film and therefore increase its performance as an actuator.[16]

The selection of electrode materials is an area of ongoing research. For our measurements, we wanted a thin, extremely low-modulus electrode that provided uniform charge distribution over the surface of the film under the electrodes. In most cases, ultrafine graphite powder and carbon blacks were brushed onto the surface of the film through a stencil. For many of the silicones that are capable of undergoing extremely large strains, it was necessary to coat these electrodes with a mixture of silicone-polymer-based graphite grease and carbon-filled silicone (Chemtronics CW7200 and Stockwell RTV 60-CON, respectively) in order to ensure full coverage at large strains. Pure graphite grease was used as the electrode material on the acrylic.

The tensile elastic modulus was obtained by measuring the force on a thin strip of polymer material at different linear strains. The compressive modulus was assumed to be equal to the tensile modulus.

EPAM Actuators Demonstration

In addition to material measurements, several actuators based on silicone and acrylic polymer films were fabricated. The performance of these actuators was measured by applying a fixed voltage across the electrodes. The applied voltage was below the maximum breakdown strength of the materials.

RESULTS

Performance Of EPAM Materials

As seen from Equations 1–3, the ideal EPAM material, with maximal energy density, has a high dielectric constant ε, a high breakdown strength (V/z), and a relatively low modulus of elasticity Y. For most applications, desirable material properties also include low viscoelastic losses, a wide range of temperature and humidity tolerance, and ease of fabricating thin films.

Table 1 shows the performance of various polymers. Relative strains are used based on the formula (actuated length – unactuated length) / (unactuated length). Table 1 shows measurements of relative area strain, electric field, modulus, and dielectric constant. The relative thickness strain is calculated from the relative area strain and the assumption of constant volume for the polymer. The pressure and elastic energy density are estimated by means of Equations 1 and 4.

Table 1. Maximum Response of Representative Elastomers (Circular Strain Test)

Polymer (Specific type)	Elastic Energy Density, $\_e$ (J/cm^3)	Pressure (MPa)	Relative Thickness Strain, s_z (%)	Relative Area Strain (%)	Young's Modulus (MPa)	Electric Field (V/μm)	Dielectric Constant (@1 kHz)
Acrylic 3M VHB 4910	3.4	7.2	–61	158	~2	412	4.8
Silicone Nusil CF19-2186	0.75	3.0	–39	63	1.0	350	2.8
Silicone Dow Corning HS3 (centrifuged)	0.098	0.3	–48	93	0.125	110	2.8
Polyurethane Deerfield PT6100S	0.09	1.6	–11	12	17	160	7.0
Silicone Dow Corning Sylgard 186	0.096	0.50	–32	47	0.7	144	2.8
Fluorosilicone Dow Corning 730 (centrifuged)	0.064	0.39	–28	39	0.5	80	6.9
Fluoroelastomer LaurenL143HC	0.027	0.65	–8	9	2.5	32	12.7
Polybutadiene Aldrich PBD	0.013	0.2	–12	14	1.7	76	4.0
Isoprene Natural Rubber Latex	0.006	0.11	–11	12	0.85	67	2.7

[a] Average engineering modulus at the maximum strain.

Several materials listed in Table 1 deserve special mention, two silicones and an acrylic. The acrylic has the greatest strain and energy density.[16] Two silicones, Nusil CF19-2186 and Dow Corning HS3, also are capable of large strains and have among the highest measured energy densities. Other materials such as polyurethane can achieve higher actuation pressures at lower voltages, due to their greater permittivity (the dielectric constant of polyurethane is roughly 7, compared to 3 for silicones). Silicone has good coupling efficiency as well as other properties, including low creep and excellent tolerance to temperatures and humidity, that make it attractive for many actuator applications. Most of our actuator development work has focused on these silicones and the acrylic.

As indicated by the values, the VHB 4910 acrylic elastomer gave the highest performance in terms of strain and actuation pressure. The performance of both the acrylic and the silicones is enhanced using high prestrains. Data indicates high prestrain increases the breakdown strength of the material and thus the actuation pressure.[16] By adjusting the prestrain, we could manipulate the performance of VHB 4910 to increase the strain while lowering the pressure. Area strains of up to 330% and thickness strains of –77% have been demonstrated using lower prestrains. However, qualitatively the acrylic elastomer has relatively high viscoelastic losses that suggest that the response would be significantly reduced at high speeds. Depending on the configuration, the bandwidth of the acrylic (50% of the full 1 Hz strain response) has been measured at 10–40 Hz. This bandwidth is adequate for many mechanical applications, it and may be further enhanced with material modifications in the future. However, it will limit high frequencies applications such as acoustic transducers. By comparison, HS3 silicone has been used for loudspeakers at frequencies of 2–20 kHz.[17,18] The actuation of CF19-2186 silicone, albeit at lower strains and fields than reported here, has been measured directly via laser reflections with

full strain response up to 170 Hz (resonance effects prevented measurement at higher speeds).[19] The only apparent fundamental limits on actuation speed are the viscoelastic losses, the speed of sound in the material, and the time to charge the capacitance of the film (electrical response time).

Comparison to Competitive Technologies

Table 2 shows several characteristics of EPAM materials and other electric actuation technologies, including several electroactive polymer technologies. The maximum strain values listed for EPAM in Table 2 are for the maximum linear, planar strain in one direction (note that Table 1 shows the area strain, which includes strain in two planar directions). The maximum linear strain is generally obtained by the use of a high prestrain in one planar direction, which causes the polymer to actuate primarily in the softer, orthogonal planar direction. The coupling efficiency for EPAM is based on treating the material as a variable capacitance.[19] This estimate is expected to be accurate for the silicone but may be an overestimation of the acrylic coupling because of the acrylic's higher viscoelastic losses. Nonetheless, the coupling of the acrylic is expected to be quite good at lower frequencies, and viscoelastic and resistivity measurements indicate that the maximum efficiency can be 60–80%, depending on drive conditions.

Table 2. Comparison of EPAM with Other Actuator Technologies

Actuator Type (specific example)	Maximum Strain (%)	Maximum Pressure (MPa)	Specific Elastic Energy Density (J/g)	Elastic Energy Density (J/cm^3)	Coupling Efficiency k^2 (%)	Maximum Efficiency (%)	Specific Density	Relative Speed (full cycle)
Electroactive Polymer Artificial Muscle								
Acrylic	215	7.2	3.4	3.4	85	60–80	1	Medium
Silicone (CF19-2186)	63	3.0	0.75	0.75	63	90	1	Fast
Electrostrictor Polymer (P(VDF-TrFE)[3]	4	15	0.17	0.3	5.5	–	1.8	Fast
Electrostatic Devices (Integrated Force Array)[14]	50	0.03	0.0015	0.0015	~50	> 90	1	Fast
Electromagnetic (Voice Coil)*	50	0.10	0.003	0.025	n/a	> 90	8	Fast
Piezoelectric								
Ceramic (PZT)†	0.2	110	0.013	0.10	52	> 90	7.7	Fast
Single Crystal (PZN-PT)[20]	1.7	131	0.13	1.0	81	> 90	7.7	Fast
Polymer(PVDF)‡	0.1	4.8	0.0013	0.0024	7	–	1.8	Fast
Shape Memory Alloy (TiNi) [21]	> 5	> 200	> 15	> 100	5	< 10	6.5	Slow
Shape Memory Polymer[7]	100	4	2	2	–	< 10	1	Slow
Thermal (Expansion)**	1	78	0.15	0.4	–	< 10	2.7	Slow
Electrochemo-mechanical Conducting Polymer (Polyaniline)[6]	10	450	23	23	< 1	< 1%	~1	Slow
Mechano-chemical Polymer/Gels (polyelectrolyte)[11]	> 40	0.3	0.06	0.06	–	30	~1	Slow
Magnetostrictive (Terfenol-D, Etrema Products)	0.2	70	0.0027	0.025	–	60	9	Fast
Natural Muscle (Human Skeletal)[22]	> 40	0.35	0.07	0.07	n/a	> 35	1	Medium

*These values are based on an array of 0.01 m thick voice coils, 50% conductor, 50% permanent magnet, 1 T magnetic field, 2 ohm-cm resistivity, and 40,000 W/m2 power dissipation.
†PZT B, at a maximum electric field of 4 V/μm.
‡PVDF, at a maximum electric field of 30 V/μm.
**Aluminum, with a temperature change of 500°C.

As can be seen from Table 2, EPAM has good overall performance compared to that of competitive technologies. Its high strain and its very high specific energy density, together with its potential for fast response at good efficiencies, are particularly attractive for small robot and other mobile applications.

Performance of EPAM Actuators

A wide variety of EPAM actuator configurations have been demonstrated. Several are analogous to well-known piezoelectric configurations; others take advantage of the unique capabilities of high-strain polymer actuators. Here we briefly describe the fabrication and performance of four EPAM actuators that illustrate the range of possible designs and potential applications.

Unimorph and bimorph actuators are similar to their piezoelectric counterparts and work well with EPAM materials. Applications for unimorph and bimorph EPAM actuators include oscillating microfans, displays, and low-force robotic elements such as grippers. Strains are higher with EPAM than with competing piezoelectric materials, so higher bending angles can be achieved with shorter devices and without resorting to submicron film thicknesses. For example, bending angles approaching 360° have been achieved with 5-mm-long unimorphs. Figure 4 shows an EPAM unimorph made from silicone. The electrodes are sputtered gold on the bonded surface and carbon black on the free surface. The sputtered gold is sufficiently stiff, compared to the silicone, that the strain is much less at the gold electrode than at the carbon black electrode. The result is that the film bends toward the carbon black electrode when a voltage is applied.

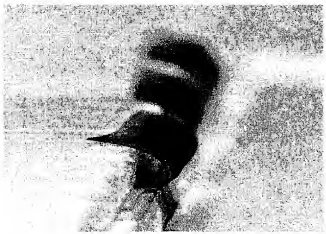


Figure 4. An Array of EPAM Unimorphs Undergoing Actuation

One possible use of unimorphs or bimorphs is to deflect light for scanner applications or optical switches. Figure 5 shows optical scanning with a 2-mm unimorph microscanner.

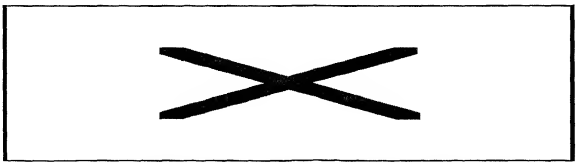


Figure 5. Optical Scanning with a 2-mm Unimorph Microscanner

The unimorph or bimorph construction is simple enough for large arrays that could, for example, be used to alter the physical properties of a surface such as in aerodynamic flow control applications.

Diaphragm EPAM actuators work very well, in part because a diaphragm can easily exploit both directions of planar expansion of the film. Figure 6 illustrates the structure of an EPAM diaphragm actuator. Diaphragms are particularly well suited for pumps but could also be used for adaptive optics, loudspeakers,[17,18] or controllable surface roughness (for example, on an aerodynamic surface). For pumps, single EPAM diaphragm actuators with up to 20 kPa (3 psi) pressure with 3-mm-diameter diaphragms have been demonstrated with silicone films. Single-layer acrylic diaphragms with diameters of up to 17 mm have produced pressures of 10 kPa. We have also demonstrated small proof-of-principle EPAM pumps using single-layer acrylic film diaphragms and one-way valves. These pumps produced flow rates of roughly 30-40 ml per minute and pressures up to 2500 Pa. Multiple cascaded pumps or thicker diaphragms could be used to increase pressure. An attractive feature of EPAM diaphragms, as opposed to piezoelectric diaphragms, is that the displacement can be relatively large without the sacrifice of other performance parameters.

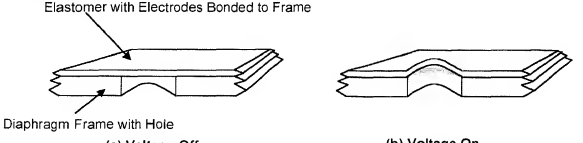


Figure 6. Diaphragm Actuator (Cross-Sectional View)

Our highest-performing films allow for out-of-plane deflection equal to 50% or more of the diaphragm diameter. Figure 7 shows an acrylic diaphragm actuator undergoing large out-of-plane deformation in which the diaphragm changes shape from flat to hemispherical. In principle, piezoelectrics can achieve large diaphragm strokes, but in practice only very thin piezoelectric diaphragms can achieve similar strokes, because the intrinsic strain of piezoelectrics is so much smaller than that of EPAM. The use of very thin piezoelectric diaphragms, however, sacrifices other parameters such as pumping pressure or packaging density, and in most cases significantly reduces the size of piezoelectric diaphragm strokes.

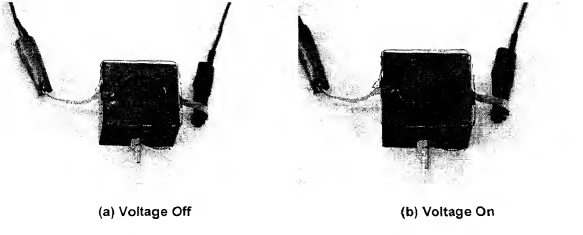
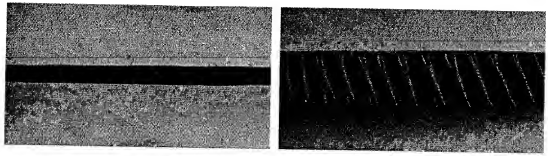


Figure 7. An Acrylic Diaphragm Undergoing Actuation

Diaphragm actuators are well suited to microdevices because they can easily be fabricated in small sizes. Arrays of diaphragms with 150 μm diameters have been demonstrated, as well as in situ fabrication of diaphragms on silicon wafers. Linear actuators can also be made in a configuration by adding a flexure that presses down on the diaphragm. We used linear diaphragm actuators to demonstrate micro light scanners, in a configuration alternative to that of the unimorph light scanner in Figure 5. Driving voltages of 190–300 V were used to demonstrate scanning similar to that in Figure 5, but at 60–200 Hz.

A **stretched film** actuator consists of a polymer film stretched over a rigid frame. The stretch can be uniform in both plane directions (as in the configuration used for strain measurement described in Section 2 and shown in Figure 3), or can be stretched much more in one direction than the other (anistropically). In the latter case, the film tends to actuate primarily in the direction with lower strain. This directional compliance effect can be combined with geometric effects to produce long, thin actuation areas that are capable of extremely large strains in the direction orthogonal to the long axis of the active area. Such an effect is shown in Figure 8. We have used this approach to produce linear strains of more than 100% in silicones and more than 200% in acrylics.

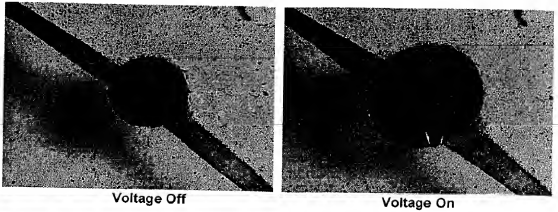


(a) Voltage Off (b) Voltage On

Figure 8. Linear-Motion-Stretched Film Actuator Showing Approximately 200% Strain

Such actuators can be used for many applications where small motions are needed, such as an optical switch in which an opaque electrode area interrupts a light beam when actuated. The advantage of this approach is that the structure is extremely simple and therefore low cost. The apparatus is basically solid state and has just one moving part, the artificial muscle film.

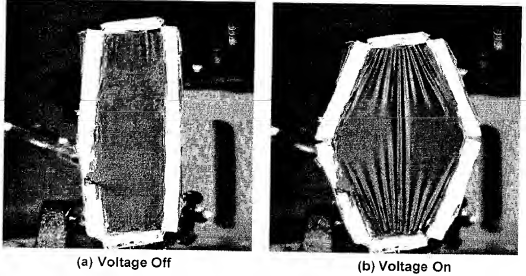
A binary switch of this type can be useful, but in some cases it may be desirable to continuously modulate the amount of light transmitted. This modulation can also be done with a stretched film actuator that uses carbon fibrils as an electrode. The fibril electrode gradually becomes less opaque as the electroded area increases. Figure 9 shows an example of such an actuator. Its advantage is the simplicity of its design compared to that of mechanical apertures.



Voltage Off Voltage On

Figure 9. Solid-State Optical Aperture Based on a Stretched Film Actuator

Bow actuators are a simple and efficient means of coupling the energy of deformation of a polymer film to linear motion.. While stretched film actuators are capable of linear motion, they do require frames. It is often desirable to include a discrete element that changes length, much like a muscle. The bow actuator uses flexures to allow the film to expand as shown in Figure 10, with suitable prestrains so that the actuation in the desired direction is enhanced.



(a) Voltage Off (b) Voltage On

Figure 10. Bow Actuator Undergoing Approximately 100% Peak Strain

The bow actuator is an example of an EPAM actuator design that specifically exploits the properties of EPAM as an actuator material. Just as optimal piezoelectric designs differ from optimal magnetic actuator designs, it is expected that optimal EPAM designs will be different from those in which other actuator materials are used, particularly because of the large intrinsic strains of EPAM.

CONCLUSIONS

Electroactive polymers based on an elastomeric dielectric between compliant electrodes show great promise for actuation. These EPAM materials show excellent overall performance and appear more attractive than many competitive actuator technologies. Strains of over 200%, actuation pressures of 8 MPa, and energy densities of 3 J/cm^3 have been demonstrated with silicone rubbers and acrylics. Their response is fast and their efficiency is potentially high. A

wide range of small devices have been made to demonstrate the potential of the technology and clarify the performance, fabrication, and actuator design issues.

The key technical issues for EPAM technology include the selection of elastomer and compliant electrode materials, the fabrication of integrated elastomer-electrode structures, and actuator design. Improved elastomer materials are an ongoing area of research, though their current performance is already attractive for many applications. Compliant electrodes have been based primarily on carbon particle materials (e.g., graphite, carbon black). Excellent-quality single-layer elastomer films can be fabricated by spin coating or commercial processes. In the fabrication area, some progress has been made in demonstrating in-situ multilayer fabrication, but at present the performance of these films is below that of films made by single-layer fabrication.

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